Analysis of Galileo Style Geostationary Satellite Imaging: Image Reconstruction

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ABSTRACT

Earlier this year DARPA announced the Galileo project, with the basic conceptual idea of using optical interferometry to combine the light from two telescopes, with one of them being movable, to image geostationary satellites. This project aims at obtaining a NIIRS 8 image of a geosat with a resolution of 10cm. The design of this experiment creates challenging issues for the reconstruction of a satellite image. Among these issues are the lack of information about the absolute phase of the baselines, the difficulty of observing with short baselines, and the time needed to obtain enough pointings to appropriately sample the UV-plane. Here we use interferometric simulations to discuss these issues.

Keywords: geostationary satellites, optical interferometry imaging, telescope arrays

1. INTRODUCTION

A major task of Space Situational Awareness (SSA) is the ability to track, identify and determine the status of any man made objects in space, to know why they are there, what they are doing now, and predict what they will be doing in the future. A critical gap in SSA capability is the ability to image deep space objects for the purposes of identification and characterization.

Deep space, all the way to the geostationary belt is a region of space where the lack of imaging capability is the most severe, representing a technology gap that must be filled. Obtaining a high-resolution image of an object at a geostationary altitude is a challenging endeavor, and the current means for observing these satellites are inadequate. There are several reasons that prevent one from reaching this goal, specifically, the size of these satellites and the amount of sunlight that they reflect.

The constraints posed by the size of these satellites create one of the hardest problems to circumvent. Geosats usually have dimensions of 10m, which means that at an altitude of 37,000 km they subtend an angle of 0.27 μrad (55 milli arcsec). Given that the best resolution achievable by a 3.6 m at 600 nm is 0.2 μrad, such observations would barely be able to measure the size of the satellite, and would not be able to obtain any detailed information about it. In fact, one can calculate that in order to observe a geosat with a resolution of 20 cm, a single telescope with a diameter of 136 m would be needed, indicating the need for optical interferometry.

However, one of the major challenges for optical interferometry is the faintness of geosats, which usually are of 11th visual magnitude or fainter. Combining these magnitudes with the fact that the typical atmospheric turbulence timescales are 10 ms, and that one needs to detect and measure the interference fringe between two telescopes on the same time scale, one needs telescope with diameters of the order of 1.5m.

DARPA has recently started the Galileo project, which aims at obtaining a NIIRS 8 image of a geosat with a resolution of 10 cm, using optical interferometry. The basic design of the experiment is to have a fixed telescope and a movable one, which will allow the observation of a large range of baseline lengths and orientations. This design, which is currently under study, will require the observation of one baseline at a time. This approach is

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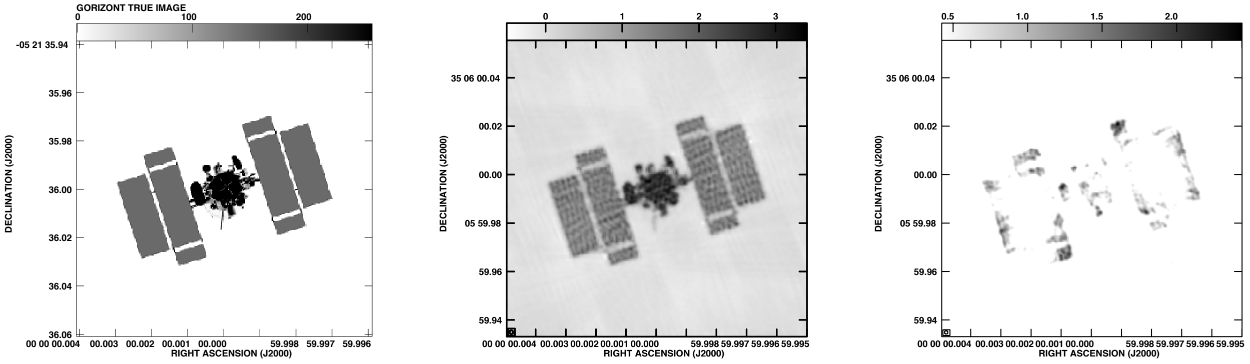

Figure 1. The original image (left), image using all baselines and assuming perfect phases (middle), image obtained using only baselines longer than 8m (right). Short baselines are needed in order to recover information about the large scale structure of the satellite.

different from the one usually employed by astronomers, where multiple baselines are observed simultaneously, and will presents a series of challenges that will be difficult to overcome. Among these challenges are: the time needed to observe a large number of baselines; the fact that the illumination angle of the satellite changes with time; the satellites and some of their components can move; the difficulty to obtain observations with short baselines (<10m); the loss of information about the absolute phase of the different baselines. Here we investigate some of these issues.

2. SHORT BASELINES

The first issue we investigate is the difficulty to observe the satellites with short baselines. For this purpose we use simulations from Ref. 4. These simulations used the image of a satellite with 15 meters, corresponding to 0.4 μradians (86 milli arcseconds) at the geostationary altitude. The simulations assumed a Y-shaped array of 21 telescopes with separations similar to the ones of the Navy Precision Optical Interferometer (NPOI) Ref. 1, corresponding to 200 baselines. This array has baselines with lengths between 2 and 98m. We used the software AIPS[5] to simulate the interferometric observations. We used simultaneous observations with 16 channels in the wavelength range 480-850 nm. We use channels with a constant width of 16.7 THz (13 nm at 480 nm, increasing to 40 nm at 850 nm). The image reconstruction was also done in AIPS using a grid of 256$\times$256 pixels with a dimension of 0.476 mas each. These simulations are noiseless, but simulations presented bellow will include noise.

In Fig. 1 we present the original image, the image obtained with all the 200 simulated baselines, and the image obtained using only baselines longer than 8m (105 baselines). We find that the image obtained using all the simulated baselines recovers most of the details of the satellite very well. The image obtained using only baselines longer than 8 m does not sample the short spacial frequencies, and the image reconstruction is not able to recover the information about the large scale structure of the source. This problem can be exacerbated if one of the dimensions of the satellite is significantly larger than 15 m. Since baselines shorter than $\sim$8 m are hard to achieve with 1.5 m diameter telescopes, this issue should be investigated in better detail.

3. ABSOLUTE PHASE

Another major challenge for the image reconstruction using observations of a single baseline at a time will be the recovery of phase information. Even if the observations are capable of recovering the relative phases

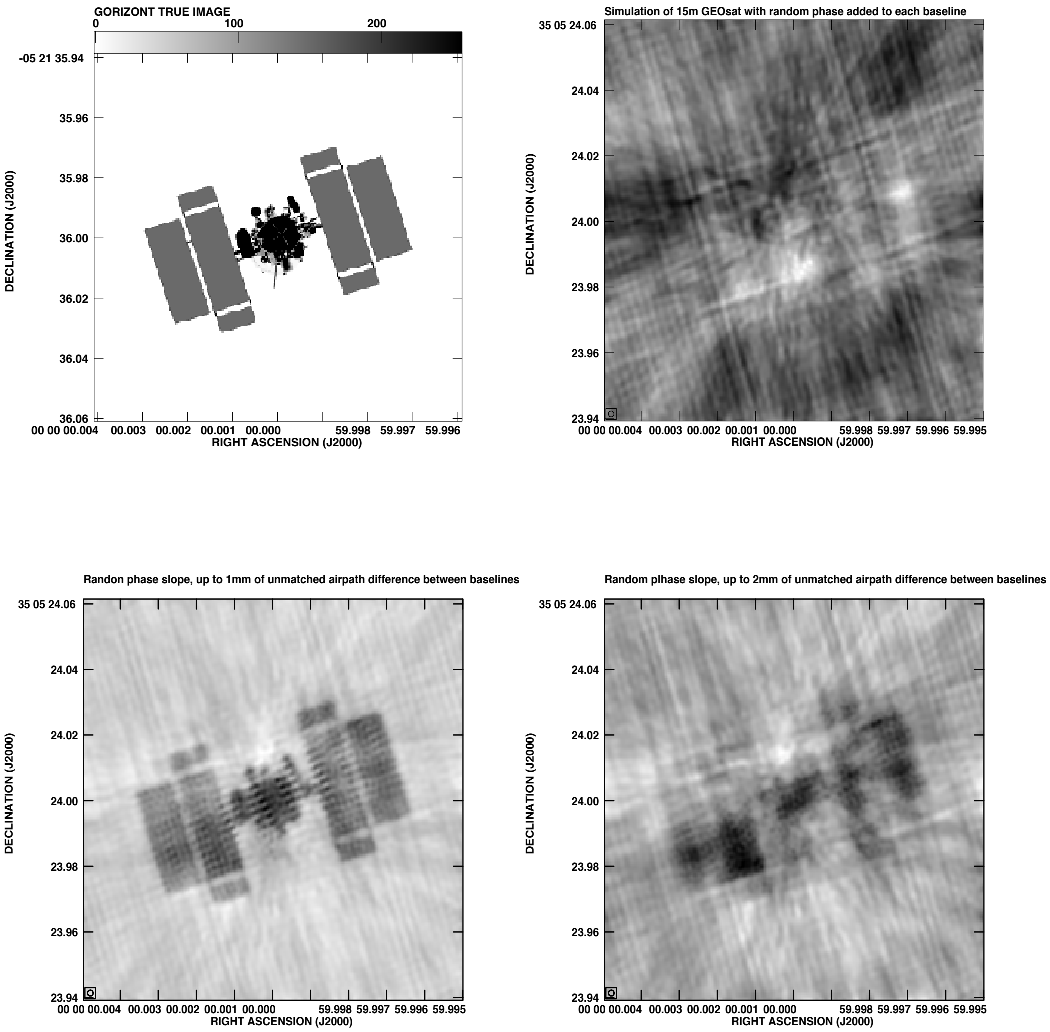

Figure 2. The top left panel shows the original image, and the top right panel shows the image obtained when the information about the absolute phases of the different baselines is not known, which will happen in the Galileo style observations. The bottom panels show the effects of an unknown phase slope across different channels. The left panel shows the case of a phase slope corresponding to a maximum extra delay of 1mm between different baselines, while in the case of the right panel the maximum delay is 2mm.

of the different channels, the atmospheric turbulence changes the object phases on a timescale of $\sim$10 ms at optical wavelengths, thus adding an unknown offset to the phases of different baselines. Using the data from the previous section, with all the 200 baselines, we simulated the effect of an unknown phase offset between the different baselines on the imaging. This was done by adding a random phase, in the range $-180^\circ < \phi \leq 180^\circ$, to each baseline. The results of this simulation are presented in the top row of Fig. 2, where we can see that by missing absolute phase information it was not possible to recover an image of the satellite.

We also explore the situation where the absolute phase of the different baselines is known, but a phase slope along the different channels is not known. These simulations were done by adding an additional random amount of air path delay between different baselines. We explored the case of a maximum airpath delay of $\pm$0.5 mm and $\pm$1.0mm. The results of these two simulations are presented in the bottom row of Fig. 2. In the case of an extra

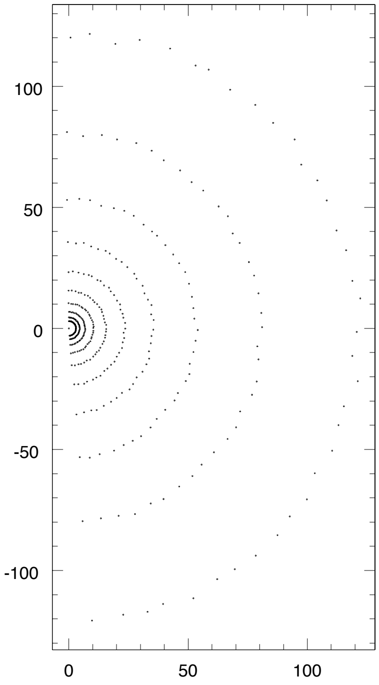

Figure 3. Positions of the movable telescope relative to the fixed one (0,0).

airpath of 1 mm (up to ±0.5 mm between different baselines), we find that the image quality gets degraded, but one can still see details about the satellite in the image. In the case of an extra airpath of 2 mm the image quality gets significantly degraded and most of the information about the satellite structure is lost.

The results from our simulations indicate the need for an alternative observing method. The way astronomers solve some of the phase effects introduced by atmospheric turbulence is by using the phase closure technique. This requires the observation of the target with 3 or more telescopes, simultaneously. Another possible way to alleviate these issues is to observe the target in a way that the long spacial frequencies sampled in a shorter baseline overlap the short spacial frequencies sampled in a longer baseline. This technique will require a larger number of baselines. Another possibility is to investigate and develop new imaging reconstruction methods, less sensitive to the limited amount of phase information.

4. INTEGRATION TIMES

The last issue we investigate is the amount of time needed to observe a target. For this purpose we developed a new set of simulations, which better represent the Galileo observational method. In Fig. 3 we show the distribution of telescope positions used for the observations. They consist of a central telescope located in the (0,0) position, while the secondary one is moved to 10 different positions along a radial direction, for 36 radial directions separated by 5°. We allowed for a random displacement of the telescopes along each position, which varies from 5 cm for the inner ring of 3 m and can be as large of 2 m for the outer ring of 122 m. Each baseline is observed with 25 channels in the wavelength range 550-950 nm, with channel widths of 9.5 THz (9.6-28.6nm from blue to red). We assume that the satellite has a visual magnitude of 11 mag, and that it reflects the solar spectrum without a wavelength dependence for different for satellite parts. We also assume that the observations are done with 1.5 m telescopes with a system throughput of 2%, and a coherence time of 8 ms, which is the integration time of each frame.

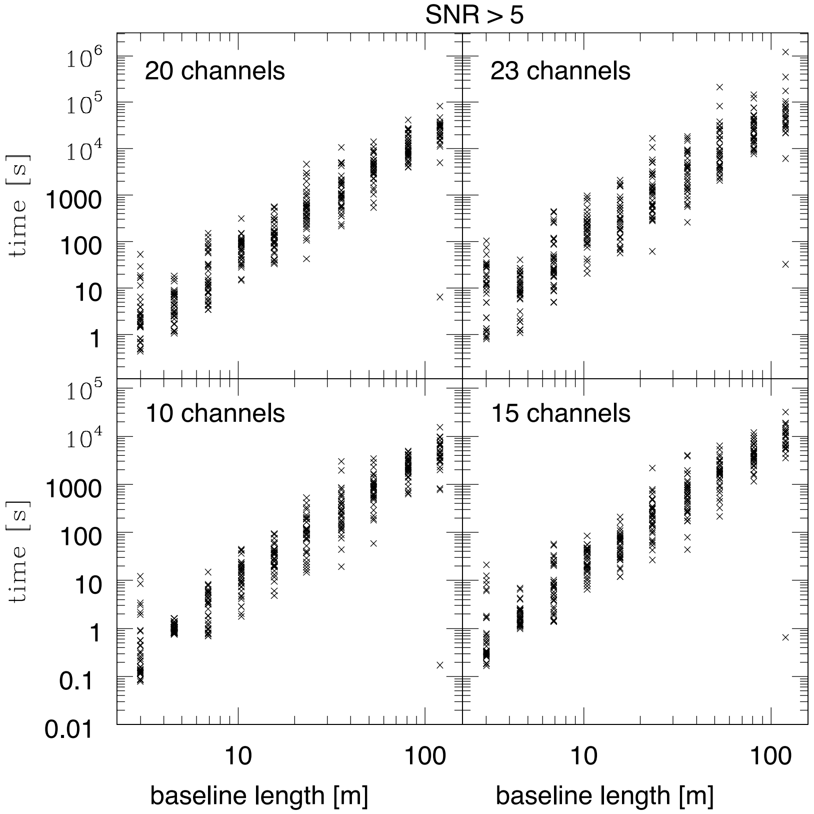

Figure 4. Exposure time needed to reach S/N=5 on baselines of different lengths. Each point along a vertical line corresponds to a different angle of the baseline. The panels show the case where only 10, 15, 20, or 23 of the 25 channels have S/N>5 (bottom left, bottom right, top left and top right panels, respectively) We find that once we cross a baseline length of 50m the integration time needed to observe these baselines with S/N=5 is of the order of 1 hour, or even longer.

These simulations are used to calculate the time needed to observe each baseline. We assume that the data can be coherently integrated Refs. 3,2, which means that $\mathrm{SNR} \propto \mathrm{MNV}^2/(1+\mathrm{MNV}^2)^{1/2}$, where M is the number of frames, N is the number of photons per frame and V is the visibility amplitude. In Fig. 4 we show the time needed to observe each baseline, in order to reach $S/N \geq 5$ in 10, 15, 20 or 23 of the 25 channels. The integration times range from less than 1s for baselines less than 5 m long, growing to a few times 10^4 seconds (hours) for baselines longer than ∼50 m.

In Fig. 5 we show the total integration time needed to reach S/N of 3, 5, or 10, on different portions of the data. We investigate the cases where 50, 75, 90 or 99% of the baselines, with 10, 15, 20 or 23 of the 25 channels are detected above a given S/N level. In the case where only 50% of the baselines are detectable above a given S/N, the total integration time ranges from less than an hour to ∼20 hours. This corresponds to a situation where only the shorter baselines can be detected, which will not allow one to reach a high spatial resolution. In order to detect most of the longest baselines, points at 90 and 99%, the total integration times needed will be of the order of 100 hours or longer. Most of this time is spent on the longest baselines, so it may still be possible to obtain a good quality image in a reasonable amount of time, although with lower resolution.

5. CONCLUSIONS

We presented simulations of optical interferometric observations of geostationary satellites. We show that in order to properly recover an image with a resolution of ∼10 cm it is necessary to observe it with both short and long baselines. The short baselines are needed to recover the information about the large scale structure of the satellite. The total integration time needed for the observations will depend on the number of channels being detected above a certain S/N, and on the resolution one wishes to achieve. For observations with a maximum baseline length of 50 m, which will result in a spatial resolution of ∼30 cm, one may be able to achieve a S/N of the order of 3 or 5 in a total integration time of the order of 10 hours, not taking into account the time needed to move and set up the telescopes. In order to achieve the best image quality with a resolution of 10 cm, one would need total integration times of hundreds of hours. Jorgensen et al. (these proceedings), present an alternative instrument design, which would be capable of imaging a geosat with a similar resolution on a much smaller time scale.

The lack of information about the absolute phase of the different baselines, or of a phase slope along wavelengths will constitute a major challenge for the proposed operational mode. A possible way to circumvent this issue is to observe the target with multiple baselines, simultaneously, or to overlap the spatial frequencies of shorter and longer baselines. The development of new image reconstruction techniques should also be considered.

ACKNOWLEDGMENTS

Basic research at the NLRB is supported by 6.1 base funding.

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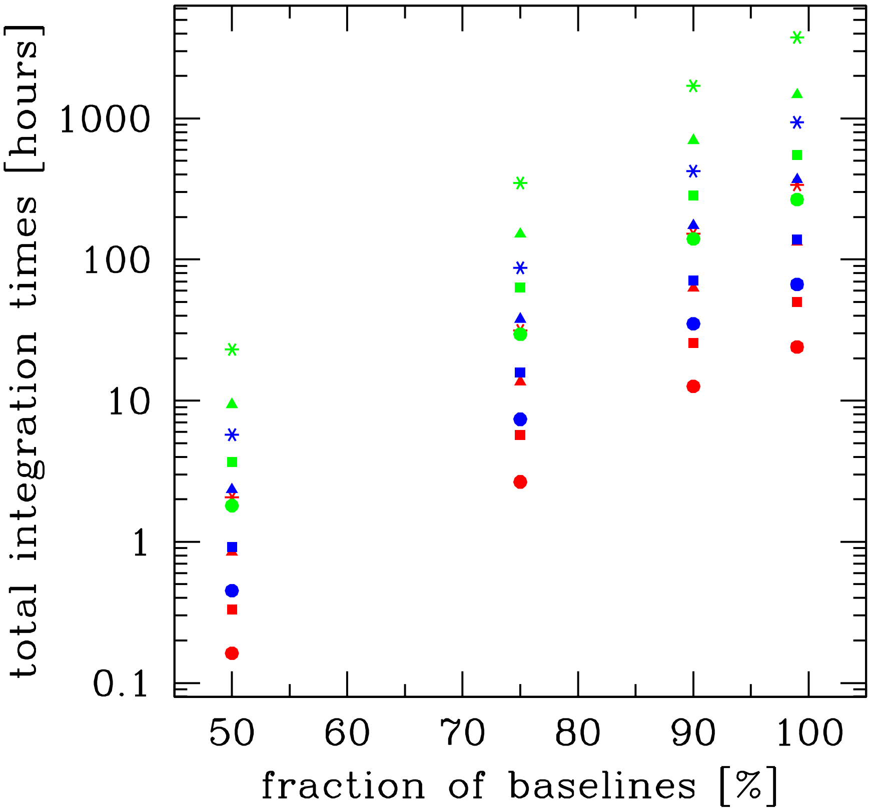

Figure 5. Total integration time, in hours. The X-axis shows the fraction of baselines being observed that reach S/N>3, 5 or 10 (red, blue and green, respectively). The different symbols (dot, square, triangle and star) correspond to a situation where 10, 15, 20 and 23 of the 25 channels of each baseline reach a given S/N.